Backscattering by Non-Spherical Natural Particles: Instrument Development, IOP'S, and Implications for Radiative Transfer

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LONG-TERM GOALS

(i) Quantify and understand the inherent optical properties (IOP's) of natural particles from a standpoint of measuring size-distribution;

(ii) Understand how the properties of particles (composition, shape, and internal structure) affect their IOP.

(iii) Incorporate these properties into radiative transfer models for prediction of downwelling and upwelling radiances.

SCIENTIFIC OBJECTIVES

We have developed the LISST series instruments that provide unprecedented quality of data on the forward scattering of light. In this project, we plan to

(*a*) develop a version of this instrument that will deliver the same high-quality data in backscatter,

(*b*) guide analytical light-scattering model development with such observations, and

(*c*) then apply the results to predicting light propagation in the sea by providing as input, the new estimates of IOP's.

This proposal is relevant to ONR's Sensor and Systems and Modeling thrust areas. It will contribute to understanding of how the shape of oceanic particles affect backscattering and provide an instrument that specifically addresses backscattering near 180 degree - a crucial parameter to understand, predict, and invert LIDAR signal. The LIDAR signal is proportional to the VSF near 180 degrees.

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14. ABSTRACT
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APPROACH

We describe the distinct tasks in the proposed program, identified with person responsible:

a. *Development of a backscatter version of the LISST instrument* (Agrawal). Shown below is a schematic diagram of the proposed instrument.

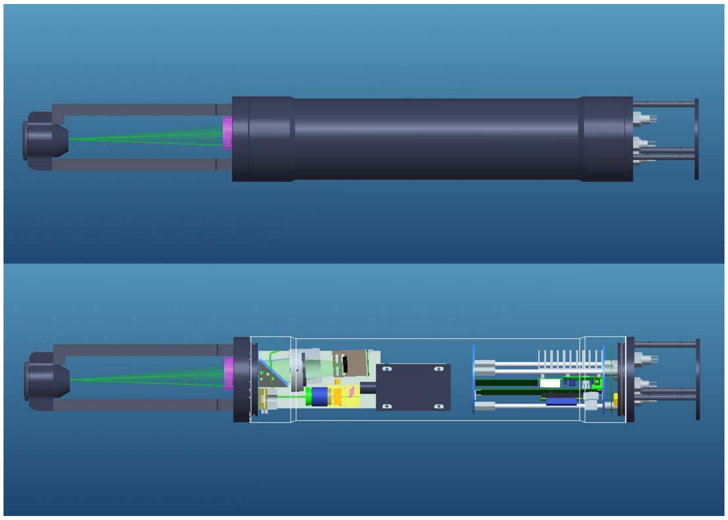

Figure 1: Engineering view of the self-contained battery powered instrument.

In light of the azimuthal structure of backscattering and polarization properties that are related to multiple scattering, we have chosen to use a CCD camera as a detector. The instrument will observe co- and cross-polarized backscatter from a 280 mW doubled YAG laser (532nm). In addition to the backscattering properties, a few photodiodes are being installed to measure side scattering along angles similar to HYDORSCAT and Eco-VSF. Optical transmission will be measured directly. These choices avoid the estimation of beam-*c* and vignetting corrections required in prior work on backscatter measurements by Maffione and Honey.(1992). An engineering schematic of the instrument is shown below as it heads to the machine shop.

Using the proposed LISST and the commercial forward-scatter versions now available, we shall attempt to constrain the overall VSF. In any case, with the detail from the new LISST, we can certainly better understand the non-spherical effects on backscatter.

b. *Characterization of scattering from terrigenous and biological size-sorted non-spherical particles* (Agrawal, Boss). The principal task is to make laboratory observations of particles sorted by settling size, as well as quantify the variability of scattering in the back-direction of different phytoplankton (with different morphologies, internal structure, and community structure (e.g. chains)).

c. *Field observations*(Agrawal)*:* We are planning a brief field deployment from the WHOI offshore observatory in the year 2005.

d. *Modeling of light scattering* (Boss)*:* Theoretical modeling of light scattering by randomly oriented non-spherical particles, using a T-matrix code similar to that used in S. Herrings thesis (Boss).

Using methods similar to Jonasz (1987a) to derive a non-sphericity index of the natural particle population under investigation and testing the possibility to obtain a non-sphericity index from measurements of polarized scattering.

e. *Modeling of Radiative Transfer* (Mobley): Incorporation of results into radiative transfer calculations. The particle VSF's and cross sections obtained from the laboratory experiments and numerical modeling of non-spherical particles will be used to generate IOPs for use as input to Hydrolight. Hydrolight will then be used to quantify the differences in predicted remote-sensing reflectance spectra for spherical and non-spherical particles.

WORK COMPLETED

Theoretical Development: A review is underway on the state-of-the-art of light scattering by non-spherical marine-like particles (75% completed). The manuscript has been approved for submission next spring in "Oceanography and Marine Biology: an Annual Review". Preliminary results focusing on backscattering were presented this fall at the Optics of Natural Waters conference in St. Petersburg, Russia. As a first cut, we have looked at a relative refractive index of $m = 1.05 + 0.01i$ (the absorption coefficient being bloated to hasten reaching the geometric optics limit) for particles with equivalent-volume spherical diameters ranging from 0.2-200 micrometers and aspect ratios from 0.1-10. From single particles, we deduce results for monodisperse populations as well as polydisperse populations using power-law size distributions compared with bi-modal log-normal size distributions (Risović, 1993). Some of the calculations are being lodged at the Cornell Theory Center supercomputing facility. A natural by-product of the work will be a database of scattering matrices for different size and shape spheroids, which we will make publicly available through an FTP site. The bulk of the work is being carried out by Wilhelmina Clavano, a PhD candidate at Cornell University, under the supervision of Emmanuel Boss.

Where the T-matrix calculations are inhibited by particles of increasing size or shape, we have substituted analytic approximations (Fournier and Evans, 1991; Kirk, 1976) to get an insight into how the IOPs behave in the large particle limit assuming the geometric optics conditions.

Backscattering is proving to be an interesting parameter both because of it being convenient for remote sensing and for the information it may provide about the properties of particles and populations of particles. Very little is tapped of the information available from the Mueller scattering matrix, much less in the full angular distribution. At the moment, we have initially scoped the possibility of matching theory to measurements of the matrix elements of light scattering by natural particles. An understanding of size and shape effects will facilitate the analysis of backscattering polarimetry, which in turn will help us understand actual measurements compared with theory.

Laboratory Observations: As a prelude to full-scale instrument design, we have carried out a set of experiments to investigate backscattering properties of spheres and natural dust. These are shown in the results section below. Spheres of various sizes and Arizona dusts (used as a standard by USGS) have been investigated. At the time of this writing, instrument mechanical and electronics system design has been completed and fabrication of components has started.

RESULTS

***Theoretical**:* While the resonance patterns are dampened in spheroids than for spheres, as expected, the angular distribution is changed so that the difference in the forward angles increase with increasing size but decrease in the backward angles (Fig. 2). We have shown that the size of the ratio of backscattering cross section of non-spheres that of spheres approaches the value of the geometric optics limit of total scattering, albeit very slowly and does not mimic the pattern either of absorption or scattering. The bulk optical properties of a given population of particles are strongly affected by its size distribution (Fig. 3 and 4). This, coupled with non-spherical shapes, results in Mie theory underestimating the IOPs when there are relatively larger particles in population. Surprisingly enough, however, the pattern of the bias in the backscattering is not evident from the biases of the other IOPs. In any case, these results suggest that an "equivalent sphere" to represent a natural particle population does not seem to exist, unless the particles are themselves spheres or close to spheres.

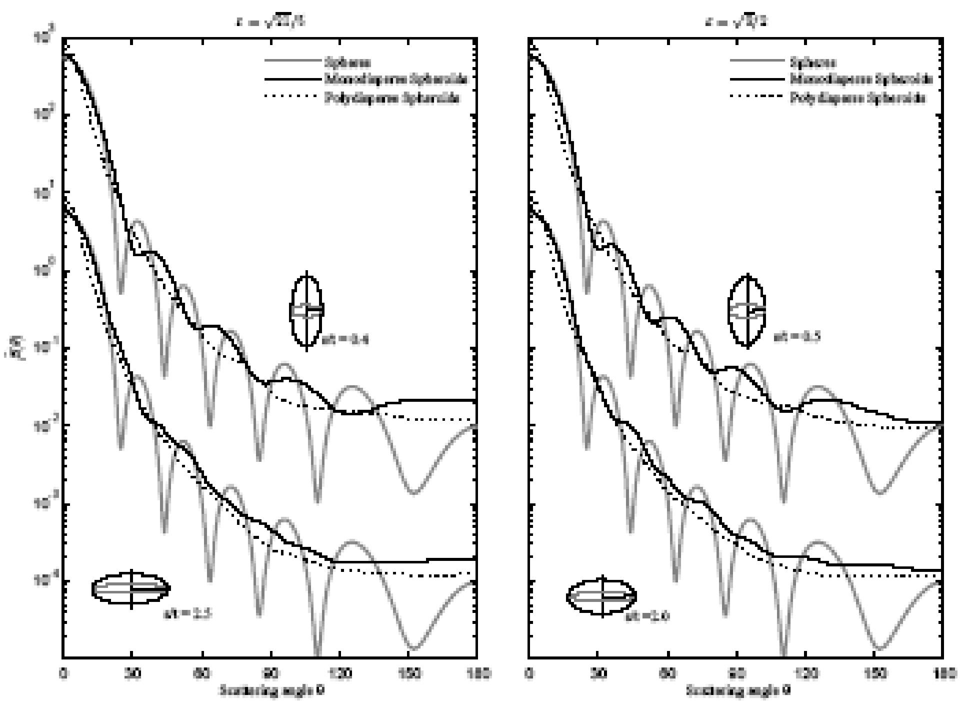

Figure 2. VSF for spheres (gray), Mono-dispersed spheroid (solid black) and poly-dispersed spheroids (dotted black) for particles of 10μm diameter, wavelength of 555nm and with index of refraction close to that of phytoplankton (n=1.05+0.01i)

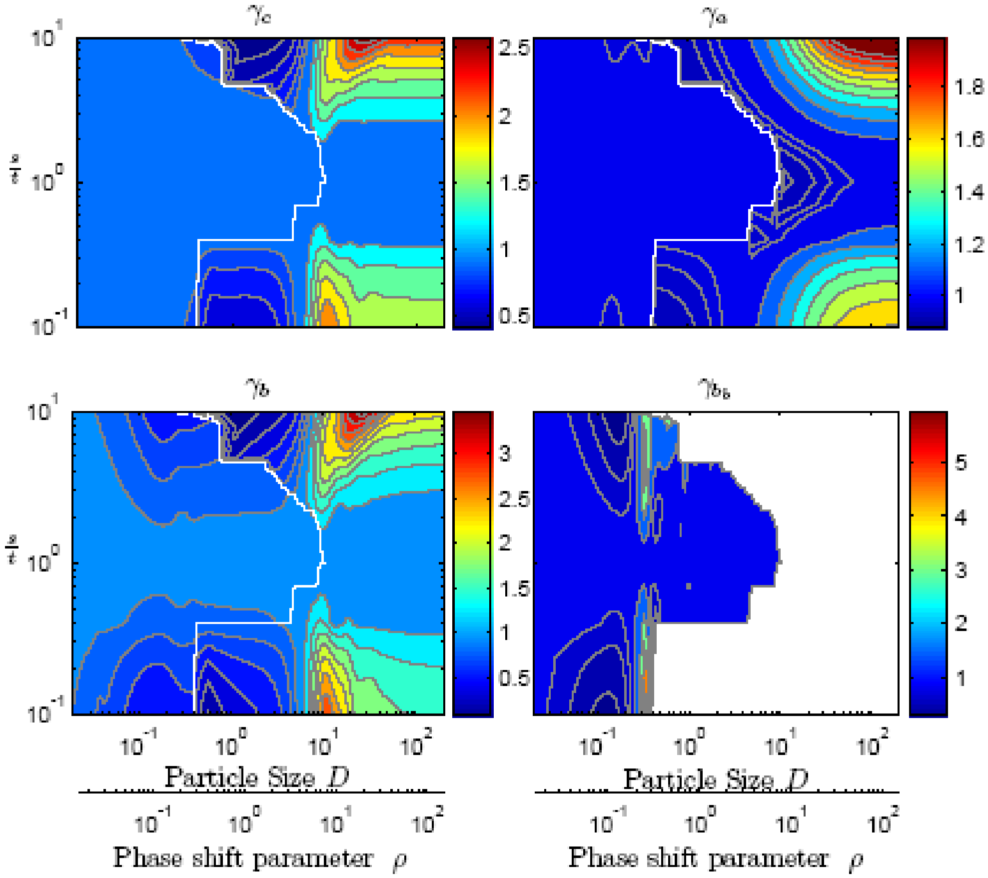

Figure 3. Bias (ratio of optical property for a spheroid relative to a sphere with the same volume) as function of size, and axis ratio (t/s axis of symmetry vs. the other axis) for attenuation (top left) absorption (top right), scattering (bottom left) and backscattering (bottom right) for a phytoplankton like particle with index of refraction n=1.05+0.01i.

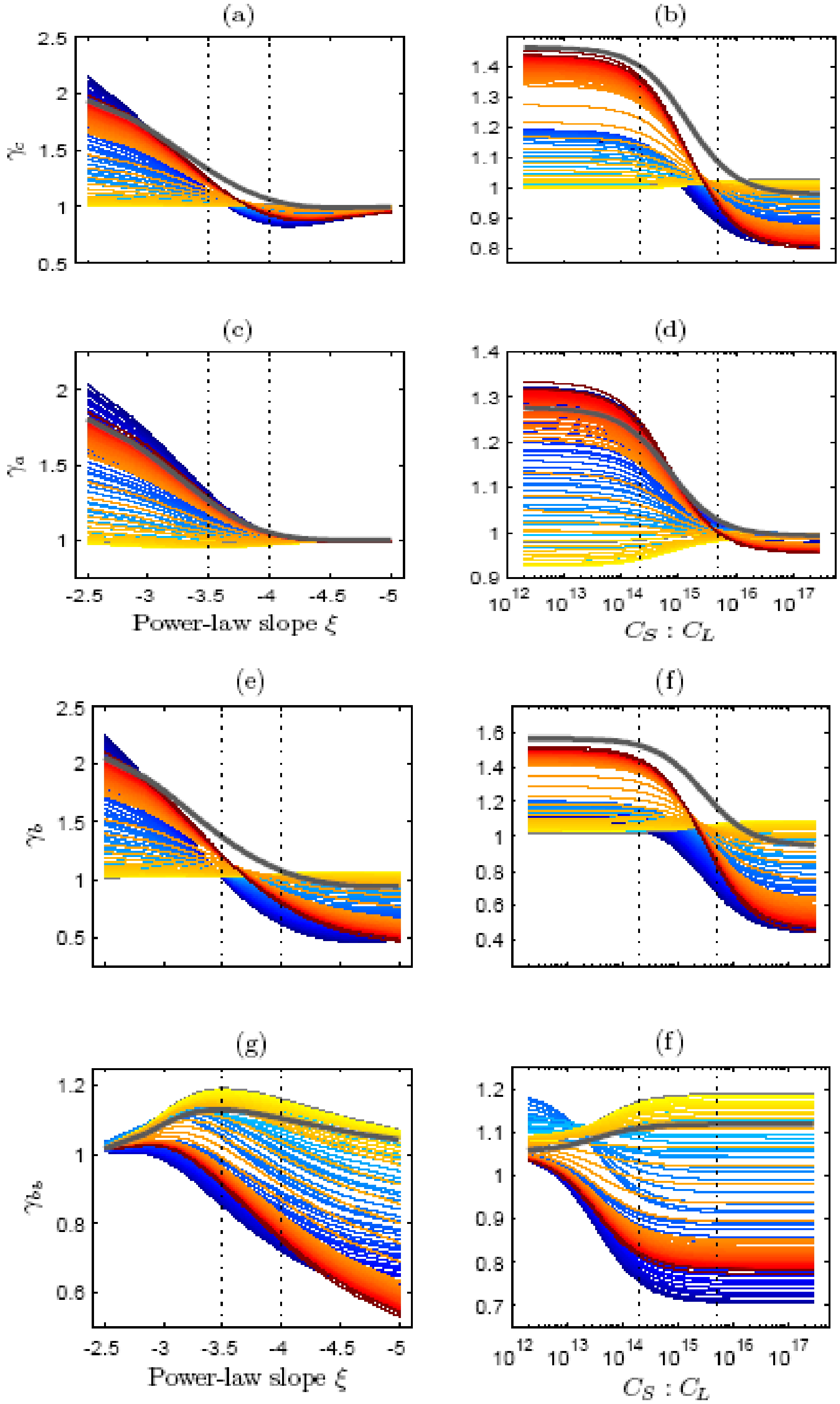

Figure 4. Bias (ratio of optical property for a spheroid relative to a sphere with the same volume) as function relative contribution of large to small particles in a population of spheroids (two population models, more large particles are on the left, more small, on the right). Spheres are the solid gray line and spheres range from extreme prolates (red) to extreme oblates (blue).

Laboratory Observations of Backscattering by Spheres and Random Shaped Particles

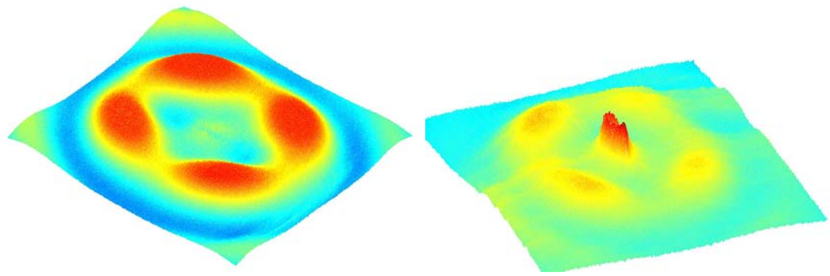

Figure 5: Intensity distributions on CCD cameras showing azimuthal variation in scattered intensity from spheres (left) and sand grains (right). Laser beam direction is vertical, out of plane of images. The azimuthal variation is maintained in the case of random shaped sand grains.

The observations above were made in the laboratory with a mock-up of the in-situ instrument. The radius of the rings represent backscatter angle, while azimuthal variation is explained by the Mueller matrix of spherical and random particles. These and similar other observations are being interpreted in light of the polarization properties and the likelihood of multiple scattering.

IMPACT/APPLICATIONS

The ability to understand the impact of shape on marine optical properties will improve our ability to interpret optical measurements in general and ocean color remote sensing in particular.

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